AFRL-MN-EG-TP-2006-7405

HYPERSONIC AND UNSTEADY FLOW SCIENCE ISSUES FOR EXPLOSIVELY FORMED PENETRATORS (BRIEFING CHARTS)

Kirk Vanden
Steve Ellison
James Wilson
Air Force Research Laboratory
Munitions Directorate
AFRL/MNAC
Eglin AFB, FL 32542-6810

Ben Case
Computational Mechanics Branch (TEAS)
AFRL, Eglin AFB, FL 32542-6810

AUGUST 2006

CONFERENCE PAPER

This paper was presented at the AFOSR Hypersonics and Boundary Layers Program Annual Review, Atlanta, Georgia, August 7-11, 2006. Three of the authors are U.S. Government employees working within the scope of their position; therefore, the U.S. Government is joint owner of the work. This paper will be published in the proceedings, and the publisher may assert copyright. If so, the U.S. Government has the right to copy, distribute, and use the work. Any other form of use is subject to copyright restrictions.

This paper is published in the interest of the scientific and technical information exchange. Publication of this paper does not constitute approval or disapproval of the ideas or findings.

AIR FORCE RESEARCH LABORATORY, MUNITIONS DIRECTORATE

- **Air Force Material Command**
- **United States Air Force**
- **Eglin Air Force Base**

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
XX-08-2006	Conference Paper	5/1/06 - 8/1/06

4. TITLE AND SUBTITLE
Hypersonic and Unsteady Flow Science Issues for Explosively Formed Penetrators (BRIEFING CHARTS)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Kirk Vanden
Steve Ellison
Ben Case
James Wilson

5d. PROJECT NUMBER
2307

5e. TASK NUMBER
AM

5f. WORK UNIT NUMBER
60

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Munitions Directorate
AFRL/MNAC
Eglin AFB, FL 32542-6810

Computational Mechanics Branch (TEAS)
AFRL, Eglin AFB, FL 32542-6810

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-MN-EG-TP-2006-7405

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Munitions Directorate
AFRL/MNAC
Eglin AFB, FL 32542-6810

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL-MN-EG

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Same as block 8

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION A: Approved for public release; distribution unlimited.
Approval Confirmation #AAC/PA 07-25-06-351

13. SUPPLEMENTARY NOTES
This paper was presented at the AFOSR Hypersonics and Boundary Layers Program Annual Review, Atlanta, Georgia, August 7-11, 2006. Three of the authors are U.S. Government employees working within the scope of their position; therefore, the U.S. Government is joint owner of the work. (Cont. on abstract below*)

14. ABSTRACT
* This paper will be published in the proceedings, and the publisher may assert copyright. If so, the U.S. Government has the right to copy, distribute, and use the work. Any other form of use is subject to copyright restrictions.

The technology of hypersonic projectiles is becoming mature from a metal physics perspective but there are still unsolved challenges relating to flight characteristics and aero dynamic stability. These projectiles deform under explosive loads and accelerate to hypersonic speeds in 2x10-6 seconds. In addition, these projectiles operate at sea-level conditions, a high-speed flight regime not commonly studied. The objective of this effort is to study the aerodynamics characteristics of deformable projectiles flying at hypersonic speeds and sea-level conditions. Because aerodynamic stability is critical for proper performance it is important to know what shapes should be avoided and which ones are acceptable. Since this was a short one-year IDP task the effort only focused on static body geometries, no deformable body calculations were attempted.
SEE ALSO AFRL-MN-EG-TP-2006-7404 FOR CONFERENCE PAPER OF SUMMARY REPORT.

15. SUBJECT TERMS
Hypersonic, Plastic Flow, Explosively Formed Penetrators, Flight Mechanics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Kirk Vanden
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	22	**19b. TELEPHONE NUMBER** *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

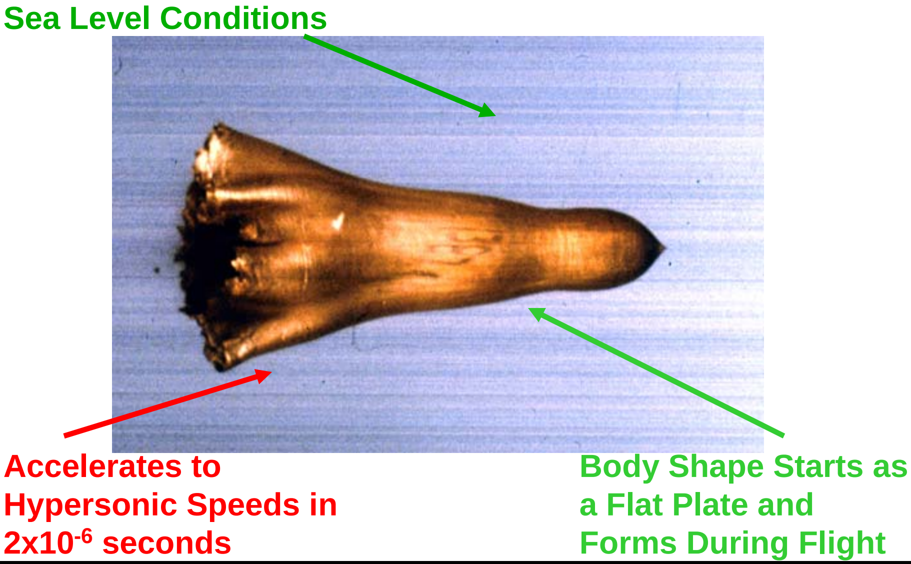
HYPERSONIC AND UNSTEADY FLOW SCIENCE ISSUES FOR EXPLOSIVELY FORMED PENETRATORS

August 2006

Kirk Vanden
Steve Ellison
Ben Case
James Wilson

Dr. Kirk Vanden
Technical Advisor
Computational Mechanics Branch
AFRL/MNAC

Hypersonics of Explosively Formed Projectiles
Munitions Directorate, Dr. Kirk Vanden



Long-Term PAYOFF: Increase stable flight distance by 100% while reducing testing costs.

OBJECTIVES

- **Quantify aerodynamic loading on a non-uniform real-time deforming geometry.**
- **Understand the degree to which aerodynamic loads affect the formation of the projectile.**
- **Determine aero-stability characteristics to help guide warhead designers. Need to increase stand-off range.**

APPROACH/TECHNICAL CHALLENGES

- **Focus on understanding the hypersonic flow physics associated with explosively formed projectiles**
- **Perform calculations to study aerodynamic stability of complex shapes under going real-time dynamic deformation.**

ACCOMPLISHMENTS/RESULTS

- **Completed initial assessment of flow chemistry**
- **Completed initial stability analysis**

FUNDING ($K)—Show all funding contributing to this project

	FY06	FY07	FY08	FY09	FY10
AFOSR Funds	50				
MNAC 6.2 Funds	200	200	200	200	200

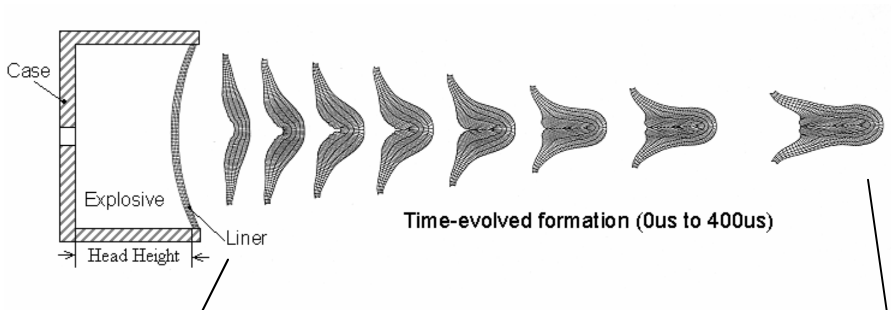
AFRL/MNAC Staff

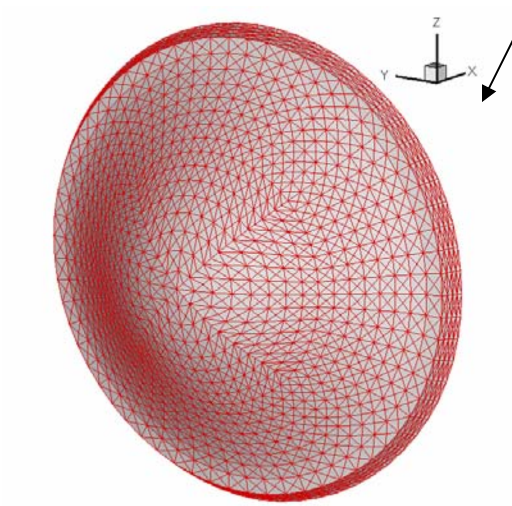
Dr. Kirk Vanden, Mr. Steve Ellison, Mr. Ben Case, Dr. James Wilson

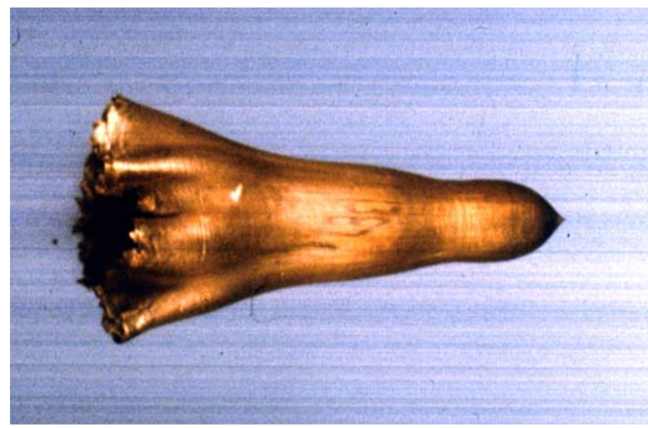
LABORATORY POINT OF CONTACT

Dr. Kirk Vanden, Computational Mechanics Branch (MNAC)

Science and Computational Challenges







- •Geometry is simpler, but deforming rapidly
- •Flow is explosively accelerated in front of body
- •No current way to quantify fluid-structure effects (metal is plastic)
- •Do not know about flow chemistry during rapid deformation
- •Cannot use static boundary conditions in CFD codes
- •Interfaces one approach to coupling with hydrocodes.

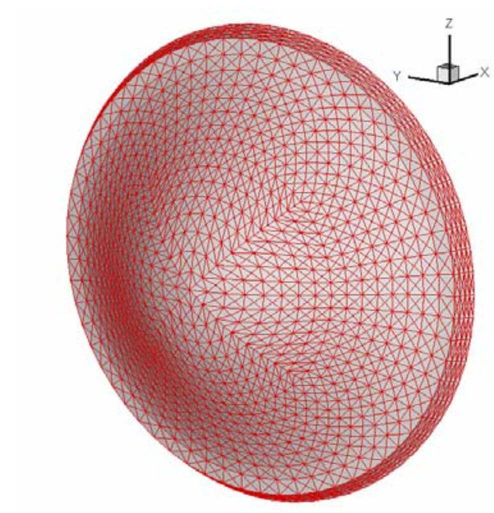
- •Geometry is complex, but deforming slowly if at all
- •Aero stability is important issue – structural failure is possible
- •Chemistry still important
- •Unsteady flow issues from base and cavity flows

Overview

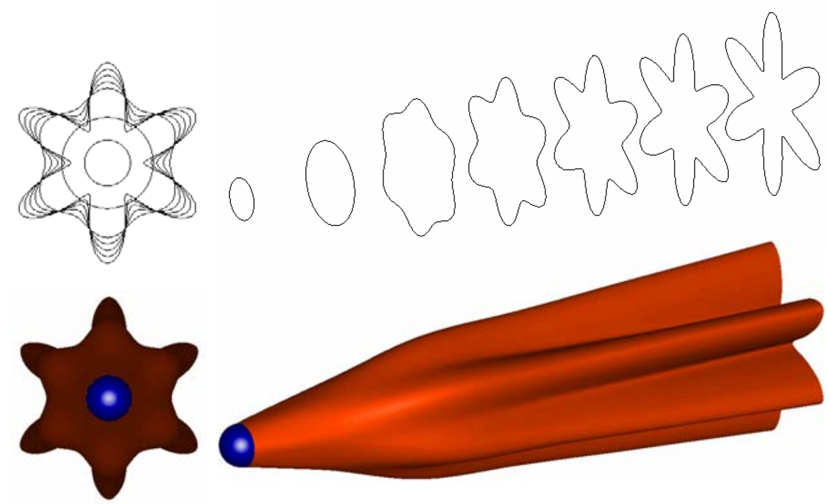
- Collaboration with AFRL/VA was Initial Plan
  - AVUS: unstructured, hypersonic CFD
  - Personnel losses delayed their participation
- Steven Ellison has brought in VULCAN (from NASA)
- Work presented here performed with Vulcan
- Still have critical need for an unstructured code, and most importantly support form the code author(s).
- Future Options
  - Obtain COBALT support through HPC IHAAA funds
  - Obtain AVUS capability if AFRL/VA is able to overcome personnel issues

Geometry

- **Aerodynamic effects on EFP formation – surface extracted from EPIC results**

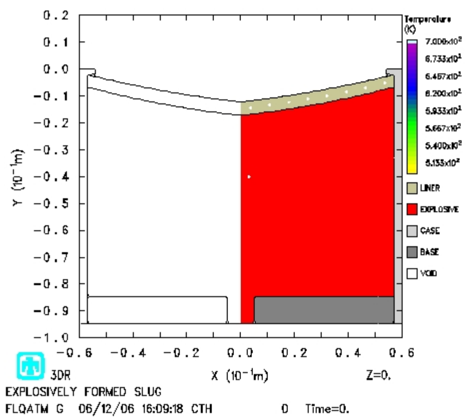


- **Long-term aerodynamic stability – analytical shape (analytical parametric equations that are lofted using CAD)**

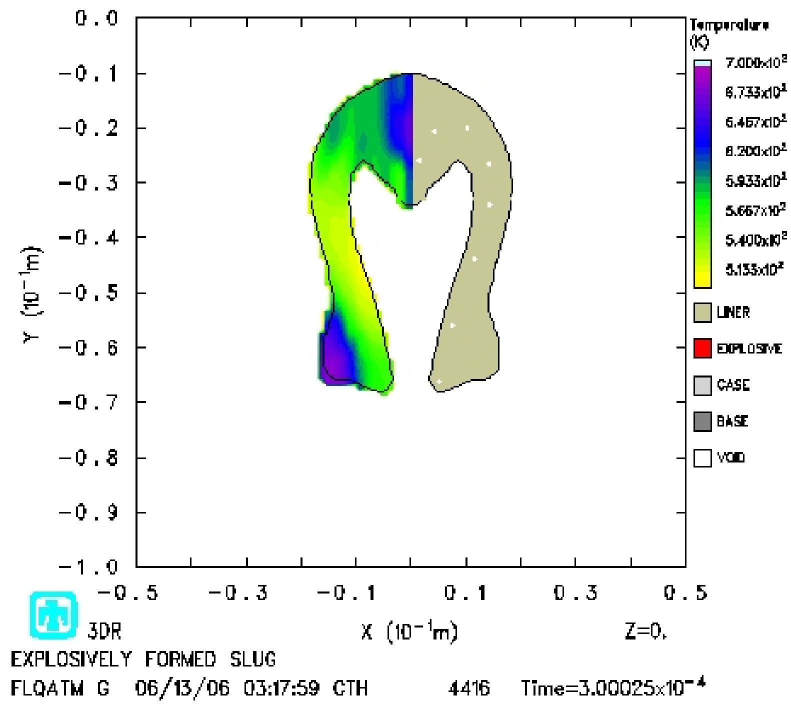


Analysis of Body Temperatures

- Performed and analysis to bound body temperatures
- Needed to see if there was heat addition to the flow from the body. Explosively deformed metal gets hot.
- Sandia's CTH Shock Physics Code was used for these simulations.
- Looked at copper and another metal



Generic Design

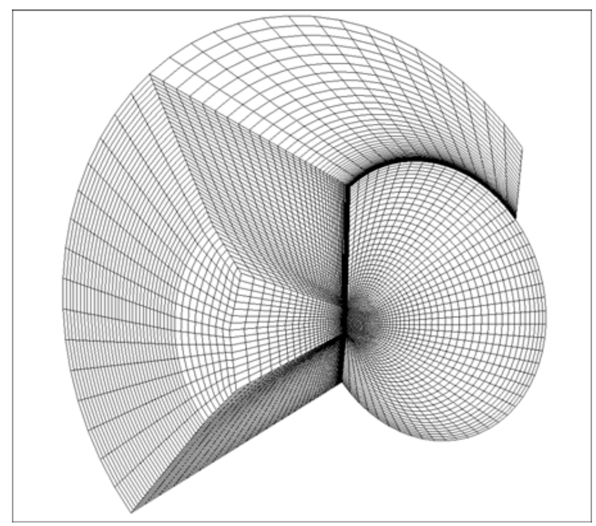


Copper

High Speed Gas Properties

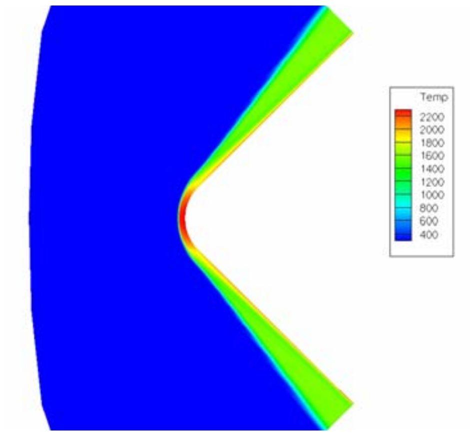
- Mach 6 at sea level
  - Ideal gas, or account for variable *g* and chemistry?
- Using Beggar
  - Ideal gas
  - Excluding base flow (outer surface only)
- Using Vulcan
  - Performed Ideal Gas, Frozen Flow, and Reactive Flow Calculations.
- Surface temperatures estimated from Sandia's CTH Hydrocode. (Courtesy of Dr. James Wilson)
  - Looked at both Copper and another metal

Mach Number	6.0
Static Density	1.225 kg/m3
Static Pressure	101325 Pa
Static Temperature	288.16 K
2-Species Simulation Mass Fractions	$f_{N2} = 0.7655$ $f_{O2} = 0.2345$
4-Species Simulation Mass Fractions	$f_{N2} = 0.7552$ $f_{O2} = 0.2314$ $f_{Ar} = 0.0129$ $f_{CO2} = 0.0005$

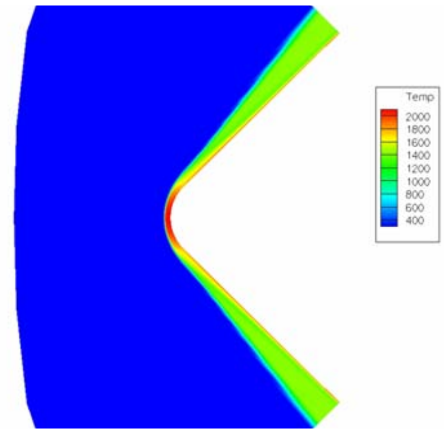


High Speed Gas Properties

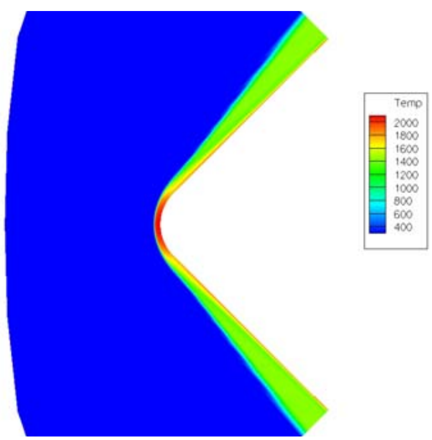
Vulcan Solutions - Temperature



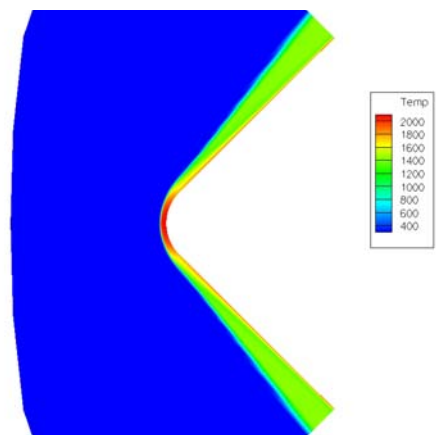
(a) Ideal



(b) 2-Sp Reacting



(c) 2-Sp Frozen

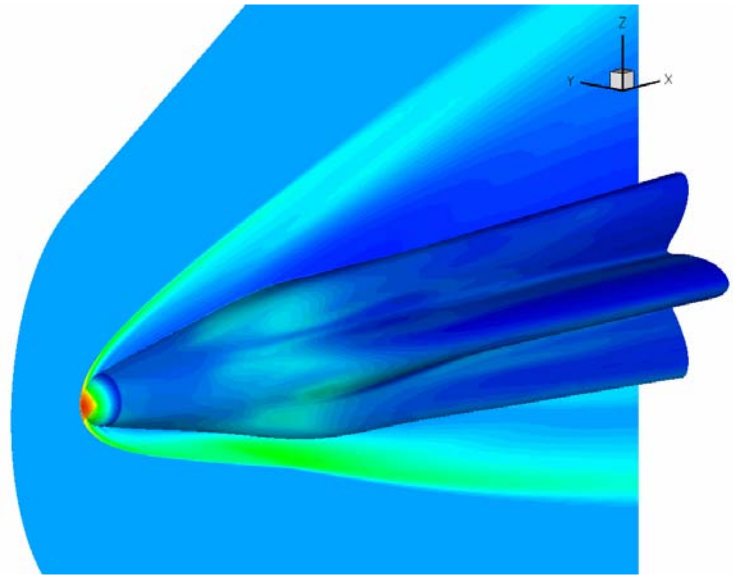


(d) 4-Sp Frozen

Numerical Experiments Performed to Determine the Level of Simulation Detail Needed to Accurately Model Low Altitude, High Speed Flows

Goal is understand what level of chemistry modeling is needed to model hypersonic flows at sea level conditions. This is critical for later analysis of aero-stability and unsteady flow issues.

Flow Parameter	Flow Parameter Range by Solution				
	Ideal Gas (Beggar)	Ideal Gas (Vulcan)	2-Species Reacting Gas (Vulcan)	2-Species Frozen Flow (Vulcan)	4-Species Frozen Flow (Vulcan)
Mach Number	0 – 6	0 – 6	0 – 6	0 – 6	0 – 6
Density	1.225 – 7.082	1.225 – 6.895	1.225 – 7.864	1.225 – 7.864	1.225 – 7.892
Pressure	1.013×10^5 – 4.752×10^6	1.013×10^5 – 4.678×10^6	1.017×10^5 – 4.736×10^6	1.017×10^5 – 4.736×10^6	1.012×10^5 – 4.710×10^6
Temperature	288.16 – 2353.2	288.16 – 2365.48	288.16 – 2091.27	288.16 – 2091.27	288.16 – 2081.27
Ratio of Specific Heats (γ)	1.4	1.4	1.294 – 1.399	1.294 – 1.399	1.294 – 1.398

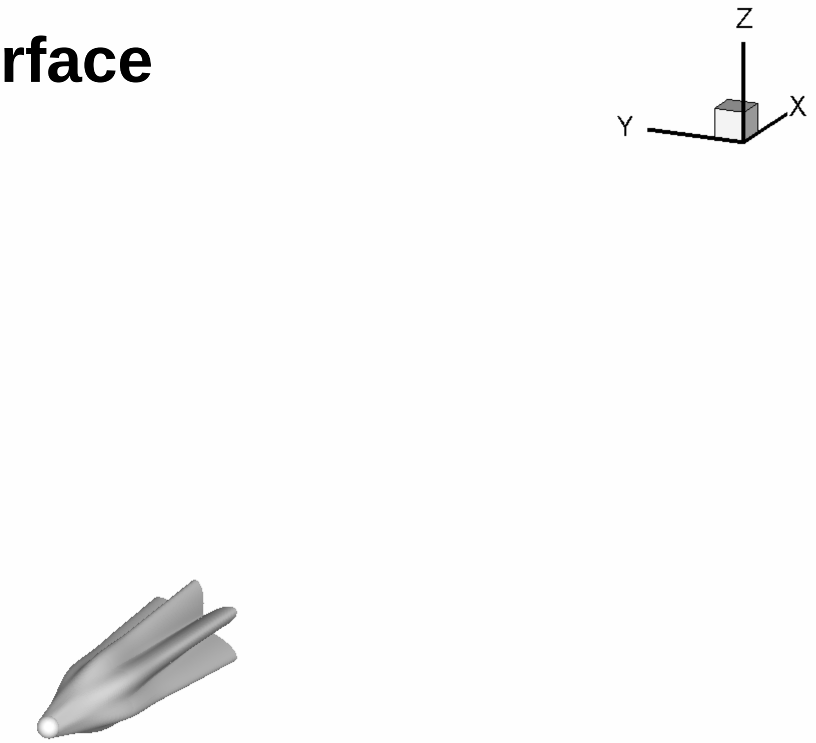


- **Ideal gas solutions had temperatures of 2350K, near the temperature diatomic oxygen begins to dissociate.**
- **A 5 species reacting gas simulation had temperatures 275K lower, and no dissociation.**
- **Frozen flow simulations with both 2-species and 4 species were calculated.**
- **It was determined that a 4-species frozen flow is an acceptable level of modeling for high-speed flows at sea-level conditions, for the current geometry.**

K. Vanden, S. Ellison, B. Case / AFRL Munitions Directorate

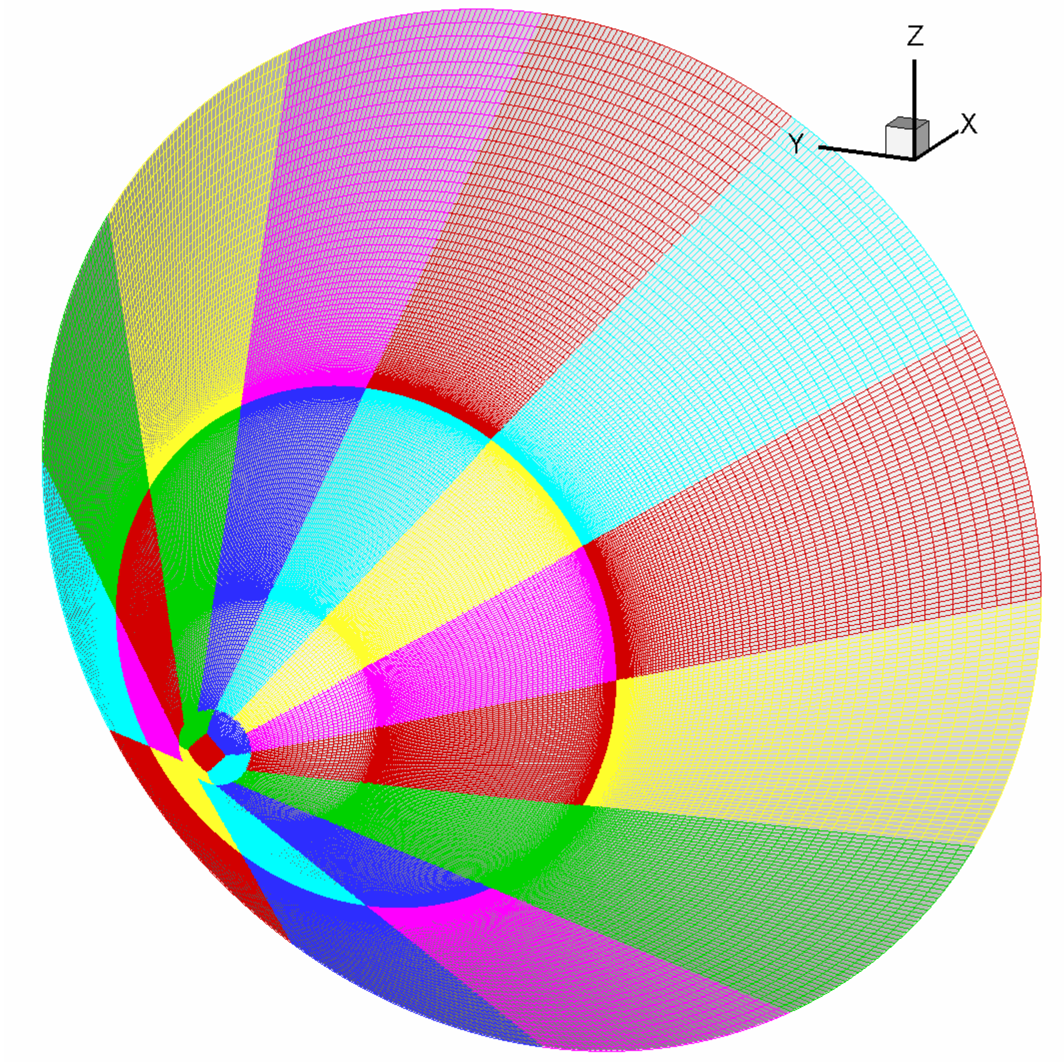
Computational Grids

- **Creating structured grids about EFP shapes…**
- **EFP Outer Surface**



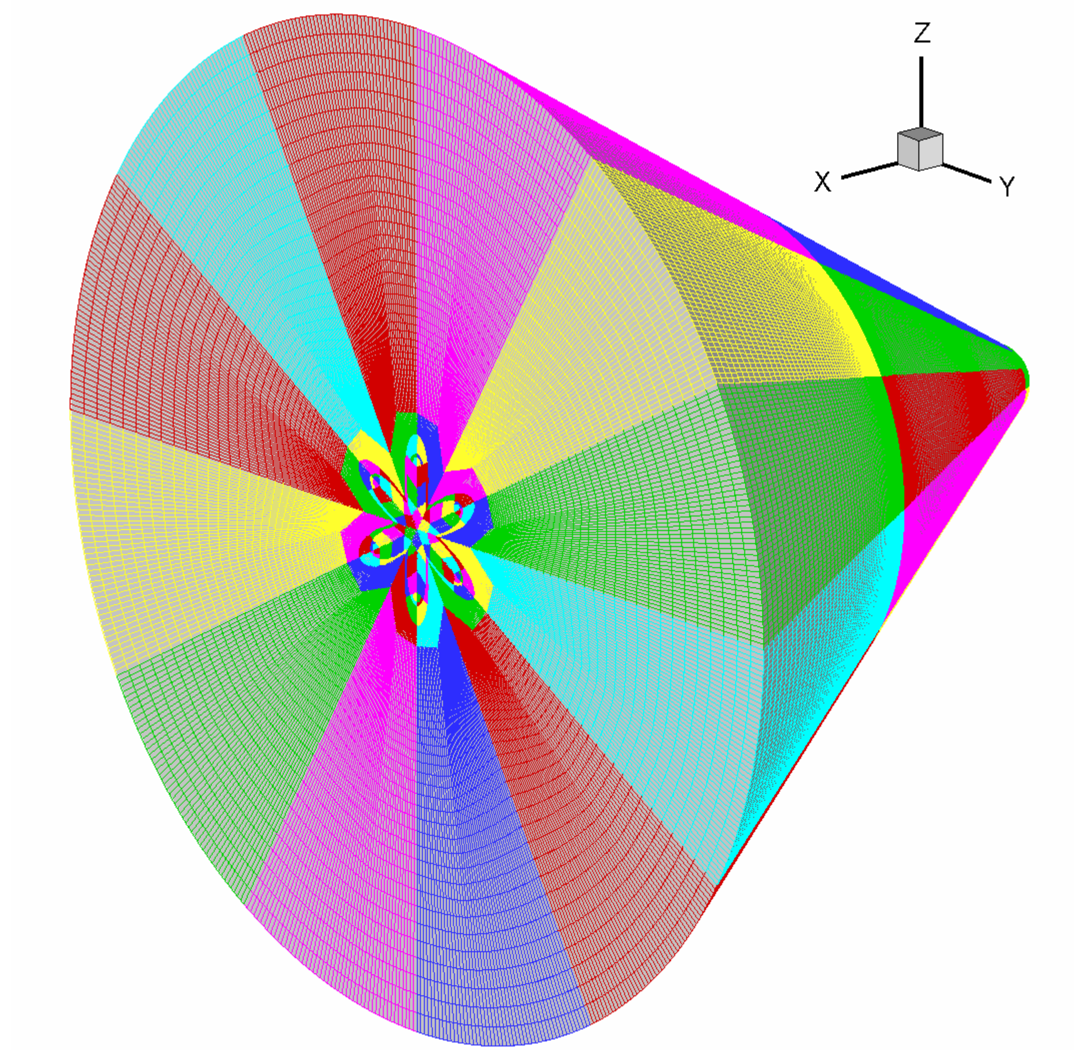
Computational Grids

- **Overview, Front**



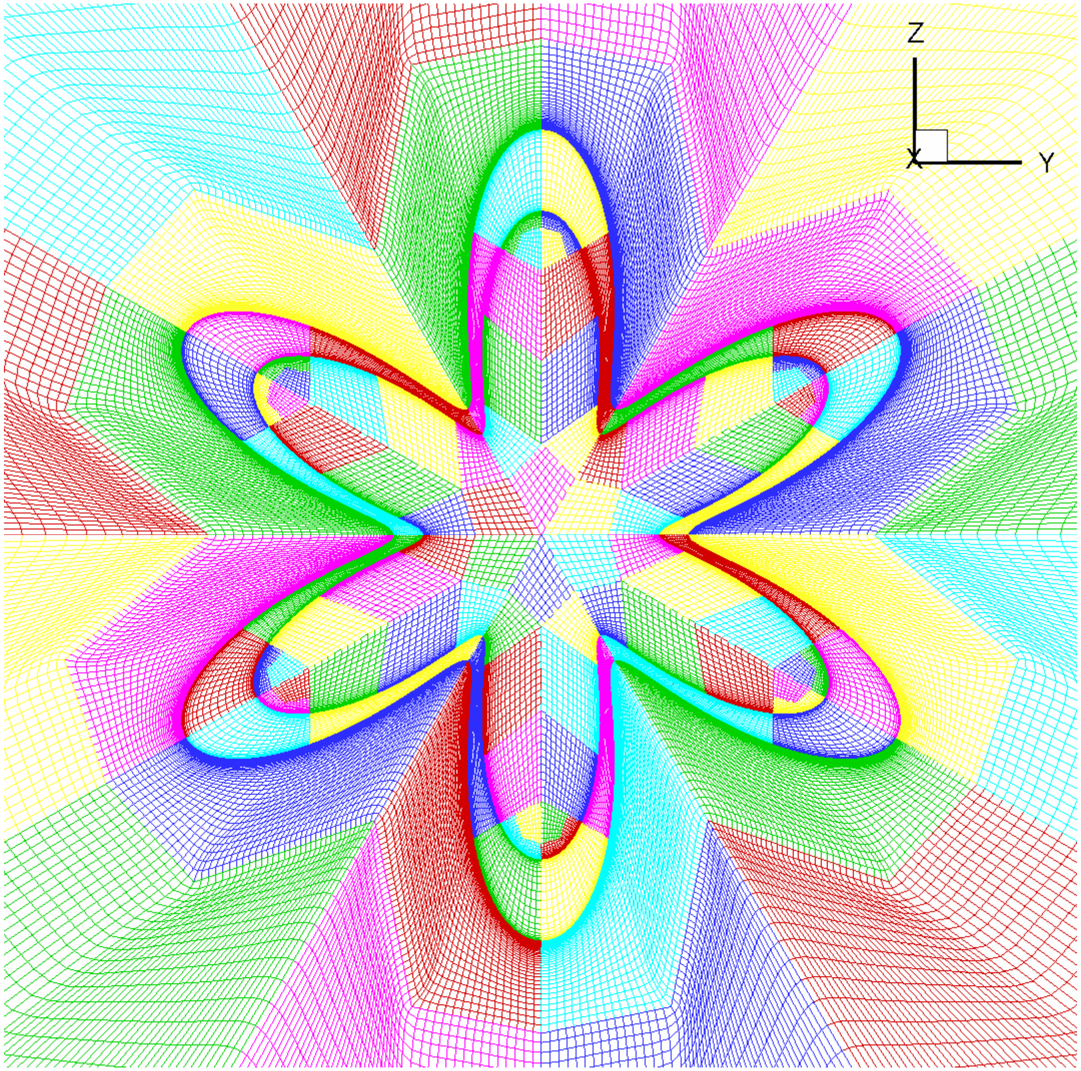
Computational Grids

- **Overview, Rear**



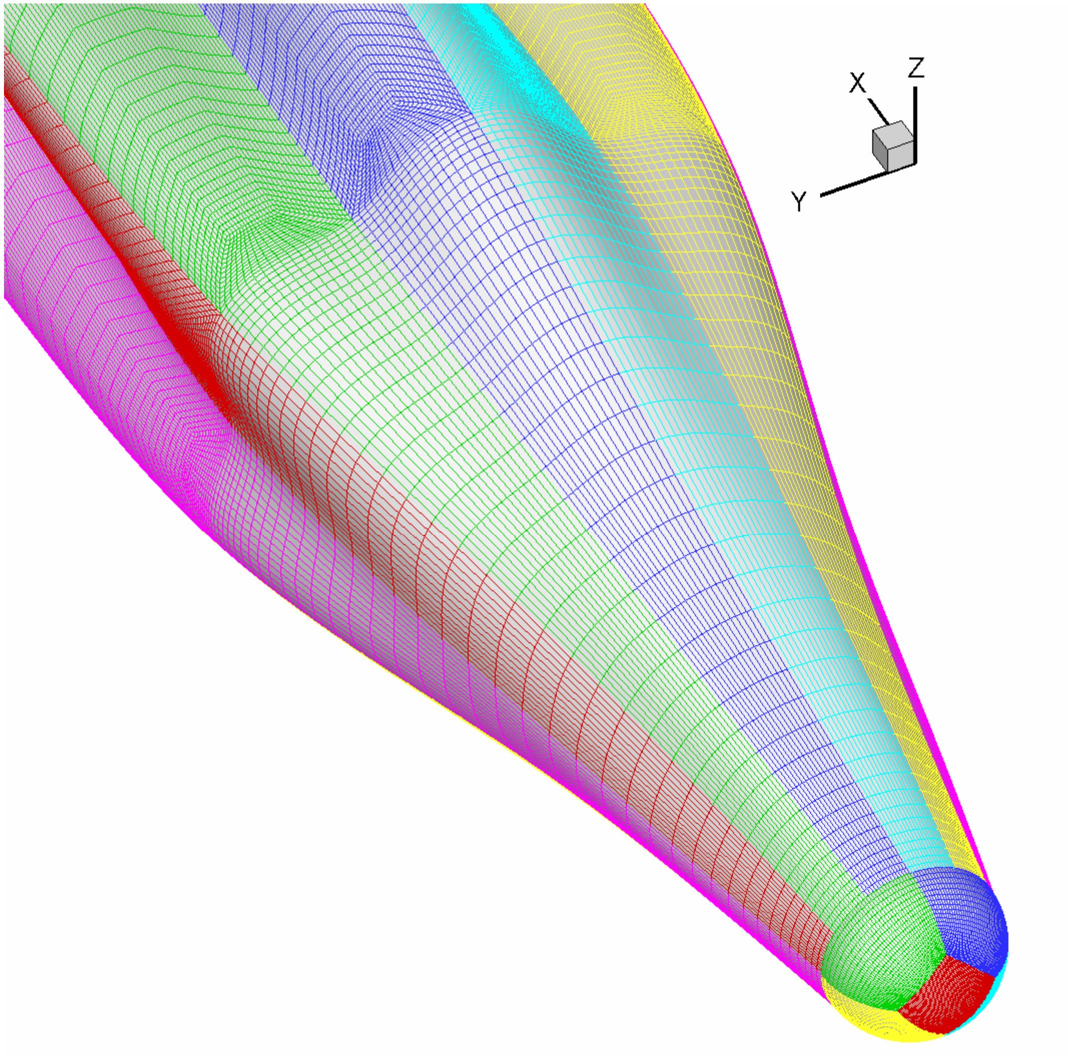
Computational Grids

- **Rear**



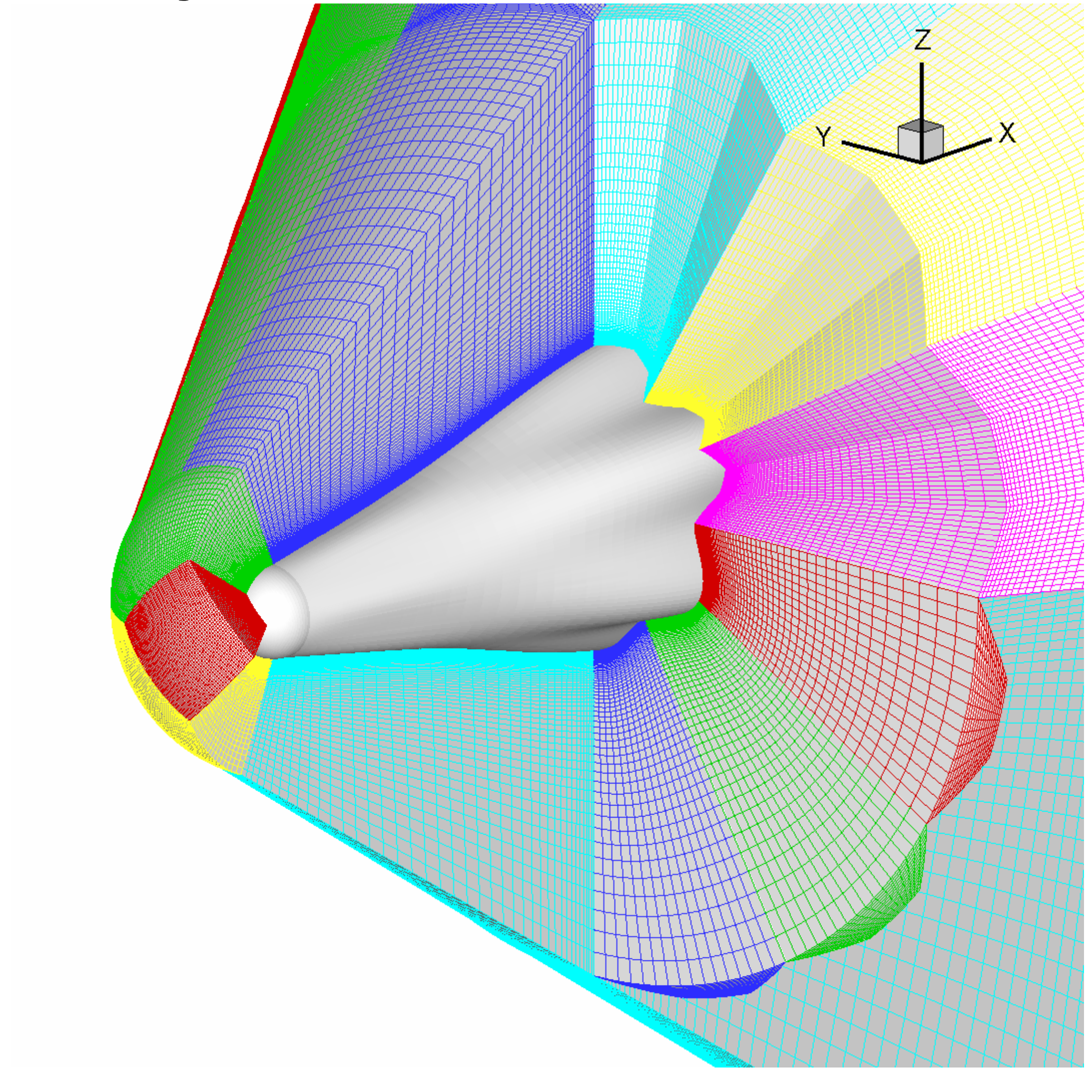
Computational Grids

- **Outer Surface Mesh**



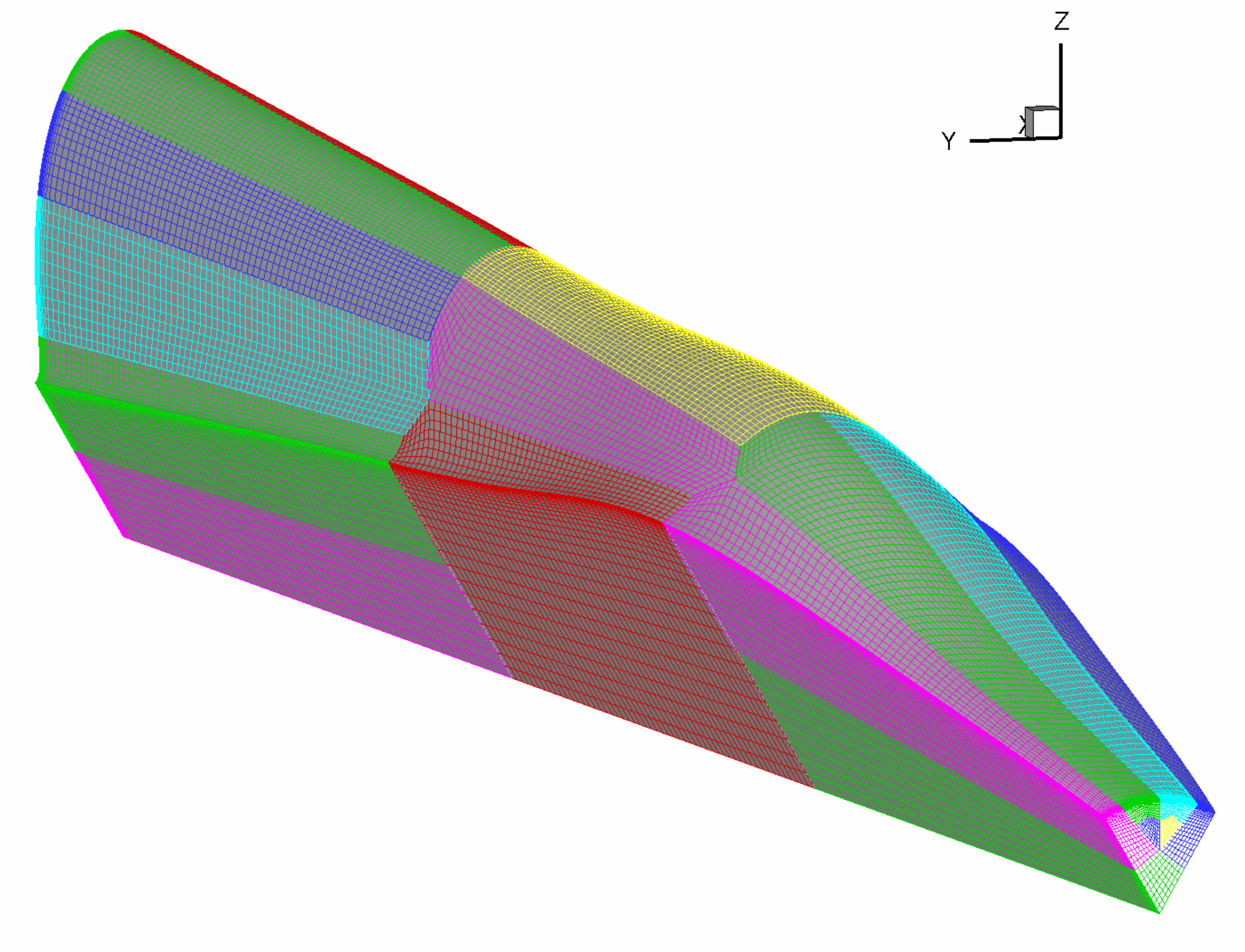
Computational Grids

- **Front Cutaway**

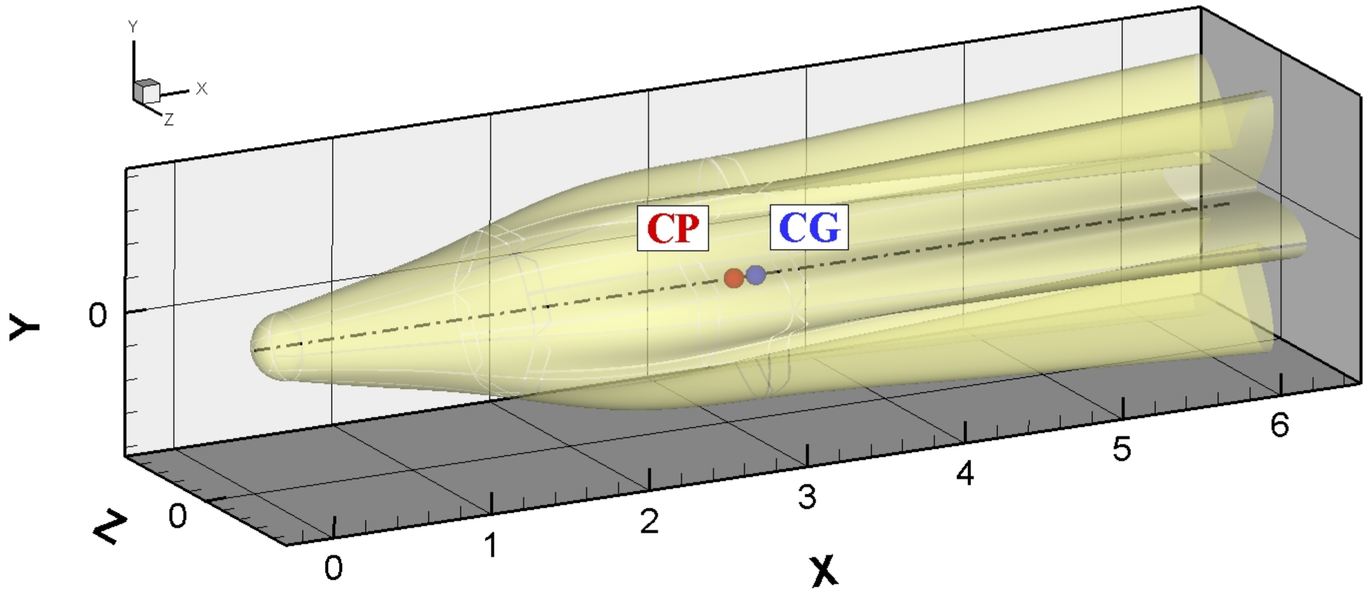


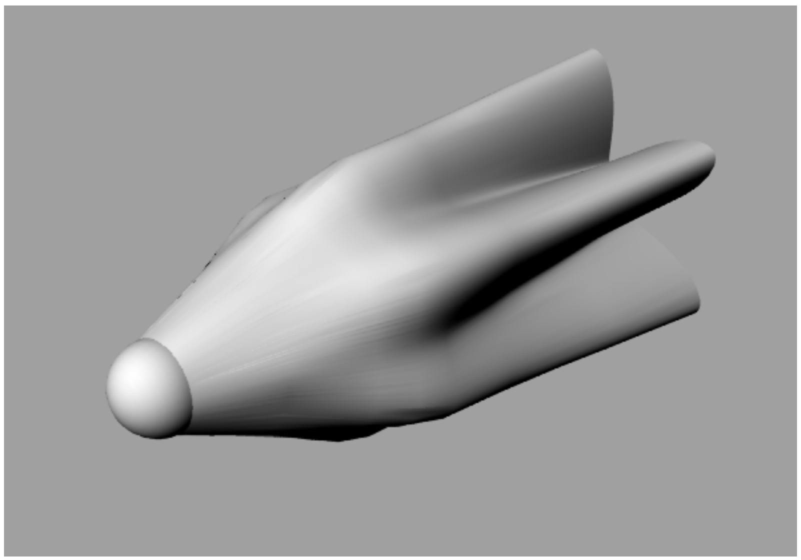
Computational Grids

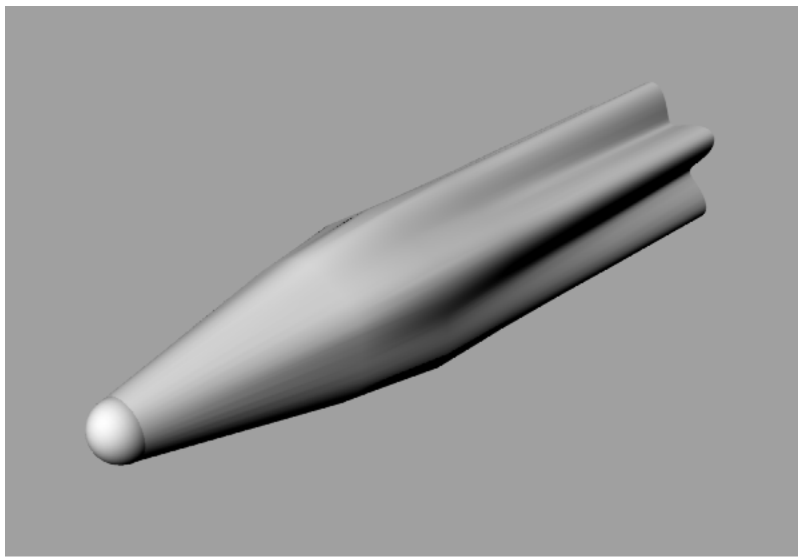
- **Cavity Mesh: 1/6 Slice**



Aerodynamic Stability







Summary

- Made advances in understanding the nature of the high speed gas dynamics.
- Too much time needed for structured grids.
  - Need unstructured capability
- Started analysis of aero-stability issues
- Performed some initial flow analysis
- Ben Case is leaving for a job in Utah.
- Appreciation for Dr. James Wilson (AFRL) who performed some solid mechanics analysis to help us.
- Appreciation to AFRL/VA for assisting us as much as they could even though they had manpower issues.

Backup Slides

Preliminary Considerations

- **Checking for adequate grid spacing by calculating the y^+ value of the first grid point off the surface.**

$$y^+ = \frac{y \rho u_\tau}{\mu}$$

$$u_\tau = \left(\frac{\tau_w}{\rho} \right)^{\frac{1}{2}}$$

$$\tau_w = \mu \frac{\partial u}{\partial y} \approx \mu \frac{V_{\text{mag}}}{\Delta y}$$

Baldwin-Lomax Turbulence Model:

$$y^+ \leq 1.0$$